## Table 3.1. Fault Data

| Fault Zone | Mechanism | Probability | Rupture Length (km) | Down-Dip Width (km) | Dip (degrees) | Slip Rate (mm/yr) | $M_W$ |
|---|---|---|---|---|---|---|---|
| **SCENARIO A ONSHORE-OFFSHORE CHANNEL FAULTS** | | | | | | | |
| **ANACAPA-DUME FAULT** | Dip-slip | 0.20[1] | 75 | 19.8 | 45 | 3.0 | 7.3 |
| **MALIBU COAST FAULT** | Dip-slip | 0.20[1] | 37 | 12.6 | 75 | 0.3 | 6.7 |
| **SCENARIO B ONSHORE-OFFSHORE CHANNEL FAULTS** | | | | | | | |
| **DUME FAULT** | Dip-slip | 0.72[1] | 60 | 19.8 | 45 | 3.0 | 7.1 |
| SANTA MONICA + DUME FAULTS | Dip-slip | 0.08[1] | 88 | 19.8 | 45 | 3.0 | 7.35 |
| **MALIBU COAST FAULT** | Oblique | 0.72[1] | 110 | 12.6 | 75 | 1.0 | 7.2 |
| MALIBU COAST + SANTA CRUZ ISLAND | Oblique | 0.08[1] | 160 | 12.6 | 75 | 1.0 | 7.35 |
| **ANACAPA FAULT** | Dip-slip | 0.80[1] | 20 | 19.8 | 45 | 1.0 | 6.5 |
| **OFFSHORE FAULTS** | | | | | | | |
| **HUENEME SEGMENT OF DUME FAULT** | Blind Thrust | 0.10[1] | 41 | 19.8 | 45 | 1.0 | 6.9 |
| **SHELF FAULT** | Blind Thrust | 0.50[1] | 56 | 19.8 | 45 | 1.0 | 7.0 |
| **SANTA CRUZ-CATALINA RIDGE FAULT** | Strike-slip | 0.25[1] | 70 | 15 | 90 | 1.0 | 7.1 |
| **SANTA CATALINA ESCARPMENT FAULT** | Strike-slip | 0.50[1] | 50 | 15 | 90 | 1.0 | 7.1 |
| **SAN PEDRO BASIN FAULT** | Strike-slip | 0.25[1] | 63 | 15 | 90 | 1.0 | 6.5 |
| **SAN CLEMENTE FAULT** | Strike-slip | 1.00[1] | 250 | 15 | 90 | 1.0 | 7.8 |
| **OAK RIDGE (Blind Thrust Offshore)** | Blind Thrust | 0.25 | 39 | 15 | 40 | 3.0 | 6.9 |
| **NORTH CHANNEL SLOPE FAULT** | Dip-slip | 0.50 | 68 | 20 | 26 | 2.0 | 7.4 |
| **ISLAND FAULTS** | | | | | | | |
| **CHANNEL ISLAND THRUST (EASTERN)** | Dip-slip | 0.25 | 63 | 14.9 | 30 | 1.0 | 7.4 |
| **SANTA CRUZ ISLAND FAULT** | Strike-slip | 0.90[1] | 50 | 13 | 30 | 1.0 | 6.8 |
| **SANTA ROSA ISLAND FAULT** | Oblique | 1.00 | 57 | 13 | 30 | 0.5 | 7.1 |
| **COASTAL FAULTS** | | | | | | | |
| **PALOS VERDES (Onshore-Offshore)** | Strike-slip | 1.00 | 96 | 13 | 90 | 3.0 | 7.1 |
| **OAK RIDGE (Onshore)** | Strike-slip | 1.00 | 49 | 13.7 | 65 | 4.0 | 6.9 |
| **MONTALVO-OAK RIDGE TREND** | Oblique | 0.25 | 36 | 10.2 | 50 | 1.0 | 6.6 |
| **VENTURA-PITA POINT** | Oblique | 1.00 | 40 | 13.6 | 75 | 1.0 | 6.8 |
| **SAN CAYETANO FAULT** | Dip-slip | 1.00 | 42 | 13 | 60 | 6.0 | 7.0 |
| **M. RIDGE-ARROYO PARIDA-SANTA ANA** | Strike-slip | 1.00 | 69 | 13 | 60 | 0.4 | 7.2 |

## Table 3.1 (Continued)

| Fault Zone | Mechanism | Probability | Rupture Length (km) | Down-Dip Width (km) | Dip (degrees) | Slip Rate (mm/yr) | $M_W$ |
|---|---|---|---|---|---|---|---|
| **INLAND FAULTS** | | | | | | | |
| **SANTA MONICA FAULT** | Oblique | 0.90 | 28 | 12.6 | 75 | 1.0 | 6.6 |
| **HOLLYWOOD FAULT** | Dip-slip | 1.00 | 40 | 12.6 | 75 | 1.0 | 6.4 |
| **RAYMOND FAULT** | Dip-slip | 1.00 | 40 | 12.6 | 75 | 0.5 | 6.5 |
| **SIMI-SANTA ROSA FAULT** | Oblique | 1.00 | 40 | 14 | 60 | 1.0 | 7.0 |
| **RED MOUNTAIN FAULT** | Strike-slip | 1.00 | 39 | 13 | 35 | 2.0 | 6.8 |
| **SANTA SUSANA FAULT** | Strike-slip | 1.00 | 27 | 13 | 55 | 5.0 | 6.7 |
| **NEWPORT-INGLEWOOD (L.A.Basin)** | Strike-slip | 1.00 | 64 | 13 | 90 | 1.0 | 6.9 |
| **NORTHRIDGE (E. Oak Ridge)** | Dip-slip | 1.00 | 31 | 13 | 42 | 1.5 | 7.0 |
| **SIERRA MADRE FAULT** | Dip-slip | 1.00 | 57 | 13 | 45 | 2.0 | 7.2 |
| **SIERRA MADRE (San Fernando)** | Dip-slip | 1.00 | 18 | 13 | 45 | 2.0 | 6.7 |
| **HOLSER FAULT** | Strike-slip | 1.00 | 20 | 13 | 65 | 0.4 | 6.5 |
| **SANTA YNEZ FAULT (East)** | Strike-slip | 1.00 | 68 | 13 | 80 | 2.0 | 7.1 |
| **SANTA YNEZ FAULT (West)** | Strike-slip | 1.00 | 65 | 13 | 80 | 2.0 | 7.1 |
| **VERDUGO FAULT** | Dip-slip | 1.00 | 29 | 12.7 | 45 | 0.5 | 6.7 |
| **SAN GABRIEL FAULT** | Strike-slip | 1.00 | 72 | 13 | 90 | 1.0 | 7.2 |
| **ELYSIAN PARK/PUENTE HILLS THRUST** | Dip-slip | 0.50 | 44 | 13 | 25 | 0.7 | 7.1 |
| **BIG PINE FAULT** | Strike-slip | 1.00 | 41 | 13 | 90 | 0.8 | 6.7 |
| **WHITTIER+GLEN IVY+TEMECULA FAULTS** | Strike-slip | 0.10 | 137 | 14 | 90 | 5.0 | 7.5 |
| **WITTIER + GLEN IVY FAULTS** | Strike-slip | 0.20 | 82 | 14 | 90 | 5.0 | 7.3 |
| **WHITTIER (W) FAULT ALONE** | Strike-slip | 0.70 | 60 | 14 | 90 | 2.5 | 7.1 |
| **SAN ANDREAS-1857 Rupture** | Strike-slip | 1.00 | 146 | 12 | 90 | 34.0 | 7.2 |

Notes: [1]Probabilities assigned to faults for this study.

### 3.2.1 Dume Fault

The Dume Fault is the dominant seismogenic source for this project. This reverse/oblique fault has a maximum dip of approximately 45 degrees and has a mapped depth of potential rupture of 20 kilometers. The Dume Fault has been mapped connecting with the Anacapa Fault by CGS (1996,2003). This is scenario A for the Dume Fault. Recent research by Sorlien et al. (2003) indicates that the Dume is truncated by the Malibu Coast Fault in mid-Channel and does not connect to the Anacapa Fault. Sorlien et al. (2003), also suggests the Dume Fault may connect with the onshore Santa Monica Fault, resulting in a small probability of a combined rupture of these two faults. This is scenario B for the Dume Fault, which treats the Anacapa Fault as a stand-alone feature.

The probability assigned to the two scenarios was 0.20 for scenario A and 0.80 for scenario B. The combined rupture of the Dume and Santa Monica Faults has been given a conditional probability of 0.10, resulting in a total probability of 0.72 for the Dume Fault alone and a probability of 0.08 of the Dume and Santa Monica Faults combined.

The eastern portion of the Hueneme segment of the Dume Fault, as mapped by Sorlien et al. (2003), is considered a blind thrust and therefore no surface expression of fault rupture is anticipated from this fault. This fault segment was given a low probability (0.10) of rupture because of the uncertainty associated with its activity, location, and nature of faulting.

### 3.2.2 Malibu Coast Fault

The Malibu Coast Fault has been mapped by CGS (1996,2003) as an onshore fault. This is scenario A for the Malibu Coast Fault. Sorlien et al. (2003) mapped the Malibu Coast as extending across the channel from the onshore segment, intersecting and truncating the Dume Fault, and connecting with the Santa Cruz Island Fault. This is scenario B for the Malibu Coast Fault. The Malibu Coast Fault is predominantly a vertical strike-slip fault with some obliquity, and has a mapped depth of seismogenic rupture of 15 kilometers.

The probability assigned to the two scenarios was 0.20 for scenario A and 0.80 for scenario B. The combined rupture of the Malibu Coast and Santa Cruz Island Faults has been given a conditional probability of 0.10, resulting in a total probability of 0.72 for the Malibu Coast Fault alone and a probability of 0.08 for the Malibu Coast and Santa Cruz Island Faults combined.

### 3.2.3 Other Faults

The Shelf Fault is a blind thrust fault that has been mapped by Sorlien et al. (2003). This fault has been imaged in seismic data and agrees with the kinematic modeling used to determine the relative motions of the faults in the northern Santa Monica Bay. There has been recent fault activity ascribed to this fault by researchers, but the overall activity rate and if this activity rate is consistent across the mapped fault plane is relatively uncertain. Because of the uncertainty associated with this fault, a probability of rupture of 0.50 was assigned in the seismotectonic model.

The San Pedro Basin Fault is parallel with and located between the Palos Verdes and San Clemente Faults. This fault has been imaged as intersecting the Dume Fault and is crossed by the Shelf Fault. The motion is thought to be predominantly strike-slip. A probability of 0.25 was assigned to this fault in the seismotectonic model because its recent activity rate is relatively uncertain.

The Bailey Fault was mapped in Jennings (1994) but not included in Petersen et al. (1996) and Frankel et al. (1996) (i.e., CGS, 1996, and USGS, 1996). This fault was originally inferred from a ground water barrier measured in well logs. A Fault Evaluation Record (FER) was performed for the City of Camarillo and found this feature inactive or not possible of seismogenic rupture for fault hazard purposes. This fault was also not included in both the California and US fault hazard mapping projects, and is not included in this seismotectonic model. The seismic hazard posed by the Dume and Malibu Coast Faults dominate the seismic hazard of this project due to both size of rupture and site-to-source distance. Given this, even if the Bailey Fault were considered active it would have limited or no significant impact on the site-specific seismicity.

# 4.0 PRELIMINARY PROBABILISTIC SEISMIC HAZARD ANALYSIS AND GROUND SHAKING

Using the seismotectonic model, probabilistic and deterministic seismic hazard analyses were performed to estimate the ground shaking parameters at four (4) locations along the proposed alignment. The four locations, shown on Plate 2.2, are:

1. At the FSRU (designated the anchor location),
2. On the pipeline route at the toe of the slope (designated south pipeline location),
3. On the pipeline route along the ridge that defines the upper slope area (designated north pipeline location),
4. At the onshore landing location.

## 4.1 SEISMIC DESIGN CODES

We understand that the design basis for the offshore BHPB facilities has not been specified by the applicable regulatory authorities nor selected by BHPB. Therefore, we have estimated the ground shaking parameters associated with the following two codes:

- The National Fire Protection Agency (NFPA) 2001 code, and
- The American petroleum Institute (API) 2000 code.

These two codes were selected because the NFPA code is used for the design of onshore LNG facilities and the API code is the code used for the design of offshore petroleum facilities. Descriptions of the seismic design basis as established by the two codes is provided below.

### 4.1.1 NFPA 59A

National Fire Protection Agency (NFPA) 59A (2001) is a guideline the recommends return periods appropriate for evaluating LNG facilities with a design life of roughly 50 years. The ground shaking was calculated for soft rock corresponding to a National Earthquake Hazard Reduction Program (NEHRP) B/C boundary. NFPA 59A Section 4.1.3 specifies the use of two levels of seismic risk in the design of LNG facilities. The two levels are termed the Operating Basis Earthquake (OBE) and the Safe Shutdown Earthquake (SSE).

The OBE is a lower-level design criterion. Qualitatively, LNG facilities are to be capable of remaining operational with minimal damage when subject to the OBE ground motions. In order to develop a design response spectrum for the OBE, it is necessary to first estimate the response spectrum for a Maximum Considered Earthquake (MCE). Per NFPA (2001), the MCE response spectrum is defined as the lesser of:

- A probabilistically estimated equal-hazard spectrum associated with ground motions that have a 2 percent probability of exceedance in a 50-year period (i.e., a return period of 2,475 years), and

- 150 percent of a deterministically estimated median response spectrum associated with the maximum magnitude earthquake on a known fault close to the site.

The MCE response spectrum ordinates should, however, not be lower than the MCE response spectrum defined by the 1997 National Earthquake Hazards Reduction Program (NEHRP) with an Importance Factor of 1, $S_s$ (short period spectral ordinate) of 1.5g, and $S_1$ (long period spectral ordinate) of 0.6g for soil conditions encountered at the site.

Once the MCE motions have been defined, the OBE ground motions are calculated as the acceleration response spectrum that is the lower of:

- Two-thirds of the spectral accelerations resulting from an MCE, and
- The probabilistically estimated equal-hazard spectrum corresponding to ground motions that have a 10 percent probability of exceedance in a 50-year period (i.e., a return period of 475 years)

The SSE is an upper-level design criterion. Qualitatively, LNG facilities are to be capable of being safely shut down with no leakage or loss of life when subject to the SSE ground motions. The SSE is calculated as the response spectrum that is the lower of:

- The probabilistically estimated equal-hazard spectrum associated with ground motions that have a 1 percent probability of exceedance in a 50-year period (i.e., a return period of 4,975 years), and
- Two times the OBE response spectrum.

The vertical component of ground shaking is determined as the calculated vertical response spectra, but not less than two-thirds of the corresponding horizontal response spectra.

### 4.1.2 API RP 2A-WSD (2000)

The American Petroleum Institute (APA RP 2A-WSD) provides a set of codes titled "Recommended Practice for Planning, Designing and Constructing Fixed Offshore Platforms-Working Stress Design." The API (2000) code applies to facilities with a design life of roughly 20 years. The ground shaking was calculated for soft rock corresponding to a NEHRP B/C boundary. The two design levels recommended by API RP 2A-WSD (2000) Section C2.3.6a, to meet strength and ductility requirements are:

1) Ground motion which has a reasonable likelihood of not being exceeded during the platform's life (typically a recurrence interval of 200 years for permanent structures in southern California), and

2) Ground motion from a rare intense earthquake (associated with an event controlled by the seismic environment that can have a recurrence interval of several hundred to a few thousand years).

In discussions with Thyl Kint of BHP Billiton on May 24, 2004, it is our understanding that a 1000-year return period is considered appropriate for the second or rare earthquake design level for this project and site. API (2000) does not provide recommendations or guidance for vertical response spectra.

## 4.2 PROBABILISTIC SEISMIC HAZARD ANALYSIS

Probabilistic seismic hazard analysis (PSHA) calculations were carried out using the computer program FRISKSP (Blake, 2000). The probabilistic assessments address:

- Exposure of the site to ground motions from multiple potential seismogenic sources, and
- The potential for the ground motions from any of these sources due to, 1) a suite of potential earthquake magnitudes (including but not limited to the maximum magnitude), and 2) a number of possible locations along the mapped extent of the source.

FRISKSP models earthquake fault sources as vertical, horizontal, or inclined planes in space and evaluates the site-specific probabilities of exceedance of given peak horizontal acceleration levels for each source, following the general procedure developed by Cornell (1968). The underlying premise is that moderate to large earthquakes occur on known Quaternary faults, and that the occurrence rate of earthquakes on each fault is proportional to the Quaternary fault slip-rate.

The length or area-of-rupture of the fault, as a function of earthquake magnitude, is accounted for, and ground motion estimates at a site are made using the magnitude of the earthquake and the closest distance from the site to the rupture zone (as a function of the attenuation relation). By summing the expected numbers from all of the modeled sources, the program calculates the total average annual expected number of occurrences of acceleration greater than each of several values requested.

By assuming that earthquake occurrence can be modeled as a Poisson process, the probability of exceedance in a specified exposure period (typically corresponding to the useful life of a project) may be estimated as follows (Yegian, 1979):

$$P[A > a,t] = 1 - e^{-[\lambda(a)t]}$$

where:

P[A>a,t] = Conditional probability of an earthquake's acceleration (A) exceeding a specified acceleration (a) during a time interval (t) given that an earthquake will occur.

λ (a) = Average annual rate of occurrence of the specified acceleration level (a) or greater.

### 4.3 HAZARD DEAGGREGATION

Hazard deaggregation is used in this analysis to determine the contribution of different magnitude events at different distances to the overall hazard. This procedure involves taking the derivative of the total seismic hazard with respect to magnitude and distance to calculate the binned contribution of each. These results are useful in identifying which faults and are contributing the most to the probabilistically estimated hazard, and what magnitude earthquakes on these faults are producing the strong ground shaking.

In this report, the results of the deaggregation are displayed as three-dimensional bar charts showing the relationship of magnitude and distance with hazard contribution. While these plots are useful for understanding hazard contribution, but can be vague when there are multiple faults at the same distance. In performing the PSHA calculations, fault specific hazard contribution was calculated and this is presented in the deaggregation discussion.

### 4.4 DETERMINISTIC SEISMIC HAZARD ANALYSIS

Deterministic estimates of the seismic hazard were calculated considering the worst-case scenario for the particular location. This involves estimating the site-to-source distance for the closest fault that has the largest rupture capacity. “Attenuation” relationships are used to estimate the ground shaking parameters. The parameters used for the Deterministic Seismic Hazard Analysis (DSHA) are:

**Table 4.1. DSHA Parameters**

| Location | Fault | Magnitude-$M_w$ | Distance-$R_{rup}$ (km) |
|---|---|---|---|
| 1. Anchor | Santa Monica-Dume Fault | 7.35 | 10.5 |
| 2. S. Pipeline | Santa Monica-Dume Fault | 7.35 | 1.5 |
| 3. N. Pipeline | Malibu Coast-Santa Cruz Island | 7.35 | 2.9 |
| 4. Onshore | Malibu Coast-Santa Cruz Island | 7.35 | 12.7 |

### 4.5 EMPIRICAL STRONG GROUND MOTION (“ATTENUATION”) RELATIONSHIPS

For the PSHA and DSHA, four equally weighted “attenuation” relationships were used. These are the same four attenuation relationships used in USGS (1996, 2002) for estimating seismic hazard for the US.

These relationships are:

1) Boore et al. (1997)
2) Campbell (1997)
3) Sadigh et al. (1997)
4) Abrahamson and Silva (1997)